Deep near-infrared observations of W3 Main star forming region

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ABSTRACT

We present a deep JHK$_s$-band imaging survey of the W3 Main star forming region, using the near-infrared camera, SIRIUS (Simultaneous three-color InfraRed Imager for Unbiased Surveys), mounted on the University of Hawaii 2.2 m telescope. The near-infrared survey covers an area of $\sim$ 24 arcmin^2 with 10 σ limiting magnitudes of $\sim$ 19.0, 18.1, and 17.3 in J, H, and K$_s$-band, respectively.

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We construct JHK color-color and J/J-H and K/H-K color-magnitude diagrams to identify young stellar objects and estimate their masses. Based on these color-color and color-magnitude diagrams, a rich population of YSOs is identified which is associated with the W3 Main region. A large number of previously unreported red sources (H-K > 2) have also been detected around W3 Main. We argue that these red stars are most probably pre-main sequence stars with intrinsic color excesses. We find that the slope of the K_s-band luminosity function of W3 Main is lower than the typical values reported for the young embedded clusters. The derived slope of the KLF is the same as that found by Megeath et al. (1996), from which analysis by Megeath et al. indicates that the W3 Main region has an age in the range of 0.3–1 Myr. Based on the comparison between models of pre-main sequence stars with the observed color-magnitude diagram we find that the stellar population in W3 Main is primarily composed of low mass pre-main sequence stars. We also report the detection of isolated young stars with large infrared excesses which are most probably in their earliest evolutionary phases.

Subject headings: ISM: clouds – stars: formation – clusters: – stars: pre-main-sequence

1. Introduction

The W3 giant molecular cloud (GMC) complex is located in the Perseus spiral arm at a distance of 1.83±0.14 kpc from the Sun (Imai et al. 2000). W3 GMC hosts two massive and active star forming regions, W3 Main in the north, and W3 (OH) in the south. The W3 Main star forming region contains objects such as H II regions, embedded infrared sources (including the extremely luminous cluster of sources W3 IRS 5), OH and water masers (Wynn-Williams et al. 1974, Forster et al. 1977, Gaume & Mutel 1987), which are in different stages of evolution.

The millimeter continuum observations have shown the existence of two dense clumps of about 2000 $M_\odot$ associated with the luminous infrared sources IRS 4 and IRS 5 in the W3 core (Richardson et al. 1989). VLA observations have resolved the IRS 5 region into a cluster of seven distinct centimeter radio sources (Tieftrunk et al. 1997, hereafter TGC97; Claussen et al. 1994, hereafter CG94). TGC97 proposed that the spatial and kinematic relation of the compact, ultracompact, and hypercompact radio continuum regions toward W3 Main is indicative of sequentially triggered star formation caused by the pressure of the expanding H II regions and the subsequent compression of the molecular gas. Recently, high resolution continuum imaging at 1.3 and 0.7 cm of four hypercompact H II regions in W3

IRS 5, suggested that these sources contain B or O stars (Wilson et al. 2003).

From a recent near-infrared (NIR) survey of a $\sim 1'.5\times1'.5$ region towards W3 Main, Megeath et al. (1996) found a dense concentration of stars in the molecular clump surrounding W3 IRS 5. These data showed a large, embedded population of intermediate to low mass stars co-existing with recently formed OB stars. They also argued that the formation of high mass stars is associated with the formation of dense clusters of low mass stars in the W3 Main star forming region. Several X-ray sources were detected in the W3 core by Chandra X-ray Observatory (Hofner et al. 2002). Most of these sources are located at the peak radio positions of the W3 H II regions. Hofner et al. (2002) postulated that the X-ray sources are the young massive stars that are also responsible for the ionization of the compact and ultracompact H II regions in the W3 core.

In this paper we present deep J, H, and K_s-bands NIR observations of the W3 Main star forming region. In comparison with the previous NIR survey (Megeath et al. 1996), our survey covers a larger area ($\sim$ 24 arcmin^2) surrounding W3 IRS 5, including compact H II regions W3 A, W3 B and W3 D, diffuse H II regions W3 H, W3 J and W3 K, and the cometary ultracompact (UC) H II regions W3 C, W3 E and W3 F. These individual H II regions have been labeled following the scheme introduced by Wynn-Williams (1971) and Harris & Wynn-Williams (1976). Our motivation is to look for new young stellar objects (YSOs) associated with the W3 Main region, to determine their evolutionary stages, and to discuss their nature. Tieftrunk et al. (1998) have presented the three $10'\times10'$ mosaics ($\sim$ 300 arcmin^2) in K' filter of W3 region. This mosaic has similar spatial resolution and depth to the SIRIUS K_s image and covers the region stretching from W3 Main to W3(OH). However, due to the crowded nature of the sources and the large pixel size, the K'-band mosaic was not suitable for photometry of the embedded stellar clusters. In Sects. 2 and 3 we present the details of observations and data reduction procedures, Sect. 4 deals with the results and discussion and we summarize our conclusions in Sect. 5.

2. Observations

The deep imaging observations of the W3 Main star forming region in the NIR wavelengths J (λ = 1.25 μm), H (λ = 1.65 μm), and K_s (λ = 2.15 μm) were obtained on 2000 August 18 with the University of Hawaii 2.2 m telescope and SIRIUS (Simultaneous three-color InfraRed Imager for Unbiased Surveys), a three-color simultaneous camera equipped with three 1024×1024 HgCdTe arrays. The field of view in each band is $\sim 4'.9 \times 4'.9$, with a pixel scale of $0''.28$ at the Cassegrain focus of $f/10$. The HgCdTe arrays work linearly within 3% upto 15,000 ADU and saturate at $\sim$ 25,000 ADU (Nagayama et al. 2003). At our K_s =

12 mag, the ADU counts are well below 15,000, thus we consider the source magnitudes to be correct within 3%. Further details of the instrument are given in Nagashima et al. (1999) and Nagayama et al. (2003).

We obtained 28 dithered exposures of the target centered at $(\alpha,\, \delta)_{2000}$ = $(02^h25^m37^s.00$, $+62°05'50''.0)$, each 30s long, simultaneously for each band and 18 dithered sky frames centered at $(\alpha,\, \delta)_{2000}$ = $(02^h25^m22^s.00$, $+62°34'41''.0)$, which is $\sim 30'$ north of the target position. The sky frame was also used as a reference field for W3 Main to assess the stellar populations within the W3 Main star forming regions (see Sect. 4). Total on-target integration time in each of the bands was 14 minutes. All the observations were done under good photometric sky conditions. We found an rms magnitude fluctuation of less than 0.05 mag in K_s-band during $\sim$ 1 hour of the observations. The average seeing in the K_s-band was $1''.2$ during the observations. The observations were made at air masses between 1.5 and 1.8. Dark and dome flats were obtained at the beginning and end of the observations. The photometric calibration was obtained by observing the standard star 9183 in the faint NIR standard star catalog of Persson et al. (1998) at air masses closest to the target observations.

3. Data Reduction

Data reduction was done using the pipeline software based on NOAO's IRAF[1] package tasks. Dome flat-fielding and sky subtraction with a median sky frame were applied. Identification and photometry of point sources were performed by using the DAOFIND and DAOPHOT packages in IRAF, respectively. Because of source confusion and nebulosity within the region, photometry was obtained using the point-spread function (PSF) algorithm ALLSTAR in the DAOPHOT package (Stetson 1987). For the JHK_s-band images the adopted fitting radii were 5 pixels ($\sim$ 1 FWHM of the PSF), and the PSF radius was 21 pixels. The local sky was evaluated in an annulus with an inner radius of 20 pixels and a width of 35 pixels. We used an aperture radius of 5 pixels ($\sim 1''.4$) with appropriate aperture corrections per band for the final photometry.

The resulting photometric data are in the SIRIUS system. For the purposes of plotting these data in color-color and color-magnitude diagrams, we have converted them into the California Institute of Technology (CIT) system using the color transformations between the

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[1] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

SIRIUS and CIT systems (Nagashima et al. 2003)[2], which have been obtained by observing several of the red standard stars of Persson et al. (1998). Absolute position calibration was achieved using the coordinates of a number of stars from the 2MASS catalogue. The position accuracy is better than $\pm 0.''7$ rms in the W3 Main field, as compared to that of the reference field ($\pm 0.''2$). The relatively poorer positional accuracy in W3 Main is probably due to a spatially varying nebulosity in the field.

The completeness limits of the images were evaluated by adding artificial stars of different magnitudes to the images and determining the fraction of stars recovered in each magnitude bin. The recovery rate was greater than 90% for magnitudes brighter than 17, 16, and 15 in the J, H, and K_s-bands respectively. The observations are complete (100%) to the level of 15, 15 and 14 magnitudes in J, H and K_s-bands respectively. The limiting magnitudes (at 10 σ) are roughly estimated to be $\sim$ 19.0, 18.1, and 17.3 at J, H, and K_s-bands, respectively. We found that within the 10 σ completeness limit, the accuracy on magnitudes of $\sim$ 98% stars in our sample is better than 0.1 mag. The sources are saturated at $K_s < 12$. For such bright sources, 2MASS PSC data were used.

We estimated the errors in photometry due to source confusion and nebulosity through artificial star experiments. The difference between the magnitudes of the added and recovered stars should reflect the effect of confusion with other stars and nebulosity. We find that for J = 19.0, H = 18.1, and K_s = 17.3 stars (at our 10 σ mag detection limit), the rms error of the difference is 0.22, 0.22, and 0.23 mag, respectively. The rms error of the difference is 0.11, 0.13, and 0.14 mag, respectively for J = 17, H = 16, and K_s = 15 stars (corresponding to the 90% completeness level). The error increases rapidly with increasing magnitude (see Fig. 6).

4. Results and Discussion

4.1. Morphology

The J, H, and K_s-band images of the W3 Main star forming region are shown in Fig. 1. The circle of a radius of 30″ (0.27 pc) marked in the H-band image represents the cluster region around W3 IRS 5 source which has been detected only in the K_s-band (see Sect. 4.6.1). The individual compact H II regions, UC H II regions, and embedded IR sources are marked in the K_s-band image. The K_s-band image shows the highest density of stars around IRS 5 molecular clump, whereas the density enhancement vanishes in the J-band image.

[2] also available at http://www.z.phys.nagoya-u.ac.jp/sirius/about/color.html

Fig. 2 shows a composite JHK$_s$ color image (J represented in blue, H in green, and K$_s$ in red) of the W3 Main star forming region. The image shows bright nebulosities towards the compact H II regions W3 A, W3 B, and W3 D. We also detect a faint nebulosity around the UC H II regions W3 C, W3 E, W3 F, and W3 G. W3 H, W3 J, and W3 K are more diffuse and dispersed H II regions. The bright blue massive stars of spectral types O and B (TGC97) are the ionizing sources of the compact and diffuse H II regions. Dark filaments extending from north-west to south-east can be seen between the diffuse nebulosity found throughout the whole image. Note the very red object near the center of the image, W3 IRS 5 ($\alpha_{2000} = 2^h25^m40^s.76$, $\delta_{2000} = +62°05'52''.5$), a deeply embedded infrared source which has been detected only in K$_s$-band. We see a dense cluster of embedded stars surrounding IRS 5. A large number of red young stars are also seen around IRS 5, which are presumably embedded in the molecular core (see Sect. 4.3).

4.2. Photometric analysis

4.2.1. Color-Color diagram

We obtained photometric data of 986 sources in J, 1236 in H, and 1512 in K$_s$-band. The drastic drop in the number of sources detected at the shorter wavelengths in spite of greater sensitivity gives the first indication of the extremely high interstellar extinction around the W3 Main region. Figs. 3a and b show the J-H/H-K color-color (CC) diagrams of the W3 Main star forming region and the reference field, respectively, for the sources detected in the JHK$_s$ bands with a positional agreement of less than 3$''$ and with photometric errors in each color of less than 0.1 mag. The reference field is also used for the correction of field star contamination from the raw K$_s$-band luminosity function of W3 Main (see Sect. 4.4). In Figs. 3a and b, the solid and broken heavy curves represent the unreddened main sequence and giant branches (Bessell & Brett 1988) and the parallel dashed lines are the reddening vectors for early and late type stars (drawn from the base and tip of the two branches). The dotted lines indicate the locus of T-Tauri stars (Meyer et al. 1997). We have assumed that $A_J/A_V = 0.282$, $A_H/A_V = 0.175$, and $A_K/A_V = 0.112$ (Rieke & Lebofsky 1985). As can be seen in Fig. 3a, the stars in W3 Main are distributed in a much wider range than those in the reference field (Fig. 3b), which indicates that a large fraction of the observed sources in W3 Main exhibit NIR excess emission. We classified the sources into three regions in the CC diagram (see e.g. Tamura et al. 1998, Sugitani et al. 2002). "F" sources are located between reddening vectors projected from the intrinsic color of main-sequence stars and giants and are considered to be unreddened and reddened field stars (main-sequence stars, giants), or Class III / Class II sources having small near-infrared excess. "T" sources

are located redward of region F but blueward of the reddening line projected from the truncated point of the T Tauri locus of Meyer et al. (1997). These sources are considered to be classical T-Tauri stars (Class II objects). "P" sources are those located in the region redward of region T and are most likely Class I objects. In Fig. 3a, a gap is seen between the reddened stars and unreddened stars (located near the main-sequence locus : H-K $\sim$ 0.4, J-H $\sim$ 1.0). By dereddening the stars on the CC diagram that fell within the reddening vectors emcompassing the main sequence and giant stars, we found the amount of visual extinction (A_V) for each star. The individual extinction values range from 0 to 24 magnitudes with an average extinction of $A_V \sim 8$ mag. The stars lying on the lower left side of the reddening band are mostly foreground stars as supported by their low values of A_V.

4.2.2. Color-Magnitude diagram

The color-magnitude (CM) diagram is a useful tool to study the nature of the stellar population within star forming regions and also to estimate its spectral types. In Fig. 4, the H-K vs K CM diagram for all the sources detected in JHK_s bands, plus some 384 stars fainter than our limit at J-band but still above the detection threshold in H and K_s-bands are plotted. The vertical solid lines (from left to right in Fig. 4) represent the main sequence curve reddened by A_V = 0, 20, 40 and 60 magnitudes, respectively. We have assumed a distance of 1.83 kpc to the sources to reproduce the main sequence data on this plot. The parallel slanting lines in Fig. 4 trace the reddening zones for each spectral type. YSOs (Class II and I) found from the CC diagram (Fig. 3a) are shown as stars and filled triangles. However, it is important to note that even those stars not shown with stars or filled triangles may also be YSOs with an intrinsic color excess, since those stars are detected in the H and K_s-bands only and are not in the J band due to their very red colors. Two bright and very red objects (K $<$ 11.5, H-K $>$ 2.8) located in the upper right corner of the figure are probably the very young stars in their earliest evolutionary phases (see Appendix and Fig. 10c and 10d). The bright infrared sources labeled with IRS numbers (Fig. 4) are associated with the molecular clumps and H II regions. These sources are shown in Table 1.

4.3. Spatial distribution of YSOs and cool red sources

In our deep NIR observations $\sim$ 40 very red sources are detected only in the H and K_s-bands. These sources have colors redder than H-K $>$ 2 in Fig. 4. They are also YSO candidates. In Fig. 5, the spatial distribution of YSO candidate sources identified in Figs. 3a and 4 are shown. Stars represent sources of T-Tauri type (Class II), filled triangles indicate

Class I sources, and filled circles denote the very red sources (H-K > 2).

In general, Class I and Class II candidates (located in the T and P regions in Fig. 3a) are distributed all over the field, however there is an apparent concentration of these sources around W3 A, W3 B, W3 F, W3 H, and W3 J H II regions as seen in Fig. 5. What is particularly striking is that most of these YSOs are associated with the diffuse ionized gas at the edge of the compact H II regions. Stars with large color indices (H-K > 2) are seen near the dense parts of the molecular cloud. Most of them are clustered near the massive molecular clumps surrounding the luminous infrared sources W3 IRS 4 and W3 IRS 5. Some of them are expected to be members of the embedded stellar cluster around W3 IRS 5. It is to be noted that these red sources are not associated with any H II regions (except the two sources south of W3 A). Therefore, these sources associated with the molecular clumps are embedded PMS stars, presumably.

The average extinction through the molecular cloud around IRS 5 that hosts the embedded cluster is $A_V \sim 15$ mag. If we assume that the large H-K (> 2) color results merely from interstellar reddening affecting normal stars, then the extinction value might even exceed 40 mag in the molecular cloud where most of the red stars are found. However, with such a large amount of absorption, diffuse emissions are unlikely to be detected in the NIR. Since most of the red sources are associated with faint diffuse emission, this provides an evidence that these sources are YSOs with intrinsic NIR excess and possibly local extinction also. In Fig. 4, a large fraction ($\sim 94\%$) of these sources are located above the straight line drawn from an A0 star parallel to the extinction vector. This suggests that they are high mass stars with circumstellar materials.

4.4. The K_s-band Luminosity Function

We use the K_s-band luminosity function (KLF) to constrain the initial mass function (IMF) and age of the embedded stellar population in W3 Main. To derive the KLF, we have determined the completeness of the data through artificial star experiments using *addstar* in IRAF. This was performed by adding fake stars in random positions into the images at 0.5 magnitude intervals and then checking how many of the added stars could be recovered at various magnitude intervals. We repeated this procedure at least 8 times. We thus obtained the detection rate as a function of magnitude, which is defined as the ratio of the number of recovered artificial stars over the number of added stars. Fig. 6 shows the rms error in the magnitude (difference between the magnitudes of the added and recovered stars) of the recovered fake stars as a function of the recovered magnitude. At $K_s = 17.3$ (10 σ detection limit), the rms error is 0.23 mag (see Sect. 3). The error is larger for the cluster than for

the whole region due to source confusion and nebulosity in the cluster region. In Fig. 7, we present the raw KLFs for the cluster of a radius of 30″ (0.27 pc) around W3 IRS 5 (see Fig. 1) and the whole W3 Main region along with the photometric completeness determined as above. We find that the completeness ratio drops below 90% at 14th magnitude and is lower for the cluster than for the whole region.

In order to estimate the foreground and background contaminations, we made use of both the galactic model by Wainscoat et al. (1992) and the reference field star count. The star counts were predicted in the direction of the reference field close to the W3 Main (see Sect. 2), which is also corrected for the photometric completeness. From Fig. 4, we conclude that the average extinction to the embedded cluster is $A_V \sim 15$ (H-K = 1). Assuming spherical geometry, then background stars are seen through $A_V \sim 30$. Therefore, in simulating the background of the region, we added an extinction value of $A_V = 30$ mag (or $A_K = 3.36$ mag) to the background stars. Then we scaled the model prediction to the star counts in the reference field, and subtracted the combined foreground (d < 1.8 kpc) and background (d > 1.8 kpc with $A_K = 3.36$ mag) data from the KLF of the W3 Main region.

After correcting for the foreground and background star contamination and photometric completeness, the resulting KLFs are presented in Fig. 8 for the cluster and whole W3 Main regions. Both the KLFs follow power-laws in shape. We estimate a total of 156 sources with K < 17.5 in the cluster region after applying the corrections for completeness and foreground and background star contamination. Given a distance of 1.83 kpc and assuming that the cluster is spherical with an apparent radius of 30″ (0.27 pc), we derive a cluster density of $\sim$ 2000 stars pc^{-3} for K < 17.5. The observed density of other embedded clusters is typically lower than $\sim$ 1000 stars pc^{-3} (Lada & Lada 2003; Carpenter et al. 1993). The high density of stars in W3 Main may be a result of the youth of the cluster and the enormous mass of molecular gas available in the W3 Main molecular core (Megeath et al. 1996).

In Fig. 8, a power-law with a slope α ($dN(m_K)/dm_K \propto 10^{\alpha m_K}$, where $N(m_K)$ is the number of stars brighter than m_K) has been fitted to each KLF using a linear least-squares fitting routine. The derived power-law slopes for various regions in W3 Main are shown in Table 2. We find that our estimate of the power-law slopes is in remarkable agreement with that of Megeath et al. (1996) in spite of the larger survey area which includes objects such as compact H II, UC H II, and diffuse H II regions. Our results therefore confirm that the KLF of the W3 Main region shows a power-law slope which is lower than those generally reported for the young embedded clusters ($\alpha \sim 0.4$, e.g. Lada et al. 1991, 1993; Lada & Lada 2003). Thus, this low value of the slope is indeed an intrinsic property of the stellar population in this region. As shown in detail by Megeath et al. (1996), the estimated KLF slopes of the whole W3 Main region are roughly consistent with the Miller-Scalo IMF if the

age of W3 population is $\sim$ 0.3–1 Myr.

4.5. Mass Estimation

Fig. 9 shows the CM diagram (J-H vs J) for $\sim$ 160 YSO candidate sources identified in Figs. 3a and 4. We estimate the mass of the sources by comparing them with the evolutionary models of PMS stars (Palla & Stahler 1999). The solid curve in Fig. 9 denotes the loci of 10^6 yr old PMS stars and the dotted curve for those of 0.3×10^6 yr old ones. Masses range from 0.1 to 4 $M_\odot$ from bottom to top, for both curves. Solid oblique reddening line denotes position of PMS with 2 $M_\odot$ for 1 Myr and the dotted oblique lines denote positions of PMS with 2 and 4 $M_\odot$ for 0.3 Myr, respectively. Most of the objects well above the PMS tracks are luminous and massive ZAMS stars (see Table 1 & Fig. 4). We use the J luminosity rather than that of H or K_s, as J-band is less affected by the emission from circumstellar materials (Bertout, Basri, & Bouvier 1988).

If we assume that the age of the stars in the W3 Main star forming region is $\sim$ 0.3 Myr, 86% of the YSO candidates detected in J, H, and K_s-bands have masses less than 4 $M_\odot$ (Fig. 9) and at least 80% of the stars have masses less than 2 $M_\odot$. Even if the age of the stars is 1 Myr, 75% of the stars have masses below 2 $M_\odot$. At the distance of 1.83 kpc, assuming an age in the range 0.3–1 Myr, and an extinction at K band between 0 and 1 mag (up to $A_V \sim$ 10), the magnitude limit (corresponding to the 90% completeness level) corresponds to M $\sim$ 0.4 $M_\odot$, according to the PMS evolutionary tracks from Palla & Stahler (1999). However, at our 10 σ mag detection limit, the mass would then go down to $\sim$ 0.1 $M_\odot$. This gives an estimate of the lowest mass limits of the detected stars in the W3 Main star forming region in our sample.

Therefore, the stellar population in W3 Main is primarily composed of low mass PMS stars. We also see the presence of lower mass stars forming a well defined cluster (e.g. near IRS 5) together with O-B type stars which have recently formed. These results support the hypothesis that the formation of high mass stars is associated with the formation of dense clusters of low mass stars (e.g. Lada & Lada 1991, Persi et al. 1994, Tapia et al. 1997).

4.6. Comments on individual sources

4.6.1. Embedded massive YSOs : W3 IRS 5 & IRS 4

The infrared sources, W3 IRS 5 (α_{2000} = $2^h25^m40^s.76$, δ_{2000} = $+62°05'52''.5$) and W3 IRS 4 (α_{2000} = $2^h25^m30^s.97$, δ_{2000} = $+62°06'20''.9$), are associated with dense molecular cores. The stellar cluster near IRS 5 has a total luminosity of about $2{\times}10^5$ $L_\odot$. The cluster of hypercompact continuum sources W3 Ma-g toward IRS 5, with diameters of < 700 AU, is situated between W3 A and B (CG94, TGC97). As seen in Sect. 4.4, we estimate a stellar density of the cluster around IRS 5 of $\sim$ 2000 stars pc^{-3} (for K < 17.5). Radio studies indicate a hydrogen density of about 10^6 cm^{-3} and a column density of about 10^{23} cm^{-2} around this source (TGC97). The source is detected only in our K_s-band image (K = 12.29 mag).

IRS 4 lies $\sim$ 80$''$ west of IRS 5 and shows a similarly high luminosity. It is associated with the hypercompact continuum source W3 Ca (TGC97). At 450 and 800 μm, the region near IRS 4 is partially resolved into two separate maxima, one near IRS 4 and the other about 20$''$ south of IRS 4 (Richardson et al. 1989, Ladd et al. 1993). None of these FIR sources coincide with prominent H II regions. The source is detected only in our H and K_s-band images (H = 15.88 mag, K = 12.96 mag).

Both IRS sources show outflow activity. These regions must be very early signposts of recent star formation. Majority of the sources located in the IRS 5 and IRS 4 regions have masses more than 2 $M_\odot$ (from Fig. 9). They are also located above the straight line drawn from an A0 star parallel to the extinction vector (Fig. 4), indicating the OB star nature.

4.6.2. The ultracompact H II regions : W3 C, W3 E, W3 F & W3 G

The W3 C UC HII region, which almost coincides with IRS 4 at the edge of the dense molecular clump, has an irregular brightened edge. W3 C is associated with W3 Ca, the hypercompact region north-east of W3 C. Most probably it is associated with the 450 μm sub-mm source SMS 2 (TGC97). Emissions at 5 and 20 μm also show a peak at W3 C (Ladd et al. 1993). The morphology of the very red nebulosity extending from W3 C / IRS 4 in Fig. 2 suggests that it is an embedded cometary-shaped H II region. The 6 cm VLA maps also show a cometary shape.

We find that a source with spectral type B0 with a shell of diffuse near-IR emission is embedded in W3 E. We designated this source as IRS N1 (see Fig.4 and Table 1). The estimated spectral type of the source matches well with that by TGC97, who find that the

Lyman continuum photon flux of ionized gas for W3 E indicates a B0.5–B0 ZAMS.

W3 F lies south-west of the dense molecular dust cloud centered on IRS 5. It is coincident with a deeply embedded infrared source IRS 7, which is detected only in the H and K_s-band images. The color and IR luminosity of this source indicate that it is a B0–B1 type star (Table 1). From the radio data TGC97 find that a ZAMS star of B0–O9.5 spectral type is ionizing W3 F.

The W3 G UC H II region is seen in radio between the two dense molecular condensations of the W3 core (TGC97). There do not appear to be any NIR sources that are associated with W3 G; however TGC97 deduced the ionizing source of spectral type B0.5–B0 ZAMS from the radio study. They argued that perhaps such an ionizing source is located behind the dense molecular gas and therefore not detected in IR.

4.6.3. The compact H II regions : W3 A, W3 B & W3 D

W3 A is a shell-like, asymmetrically edge-brightened H II region and most likely is in a late stage of its expansion (TGC97). The main part of W3 A is no longer embedded in the dense molecular gas (Roberts et al. 1997). The embedded O5–O6 stars W3 IRS 2 and IRS 2a are located close to the center of W3 A. The O6 star IRS 2b lies in the NW of W3 A. The less luminous O9–B0 star IRS 2c is located $\sim 40''$ east of IRS 2. The spectral types of these objects are estimated from the CM diagram (Fig. 4) based on their colors and IR luminosities. These massive stars are collectively responsible for the ionization of the W3 A H II region. Despite the number of these bright sources, we find a low number of low-mass YSOs in this H II region (Fig. 5), which may be due to confusion with the high surface brightness of the diffuse nebulosity of W3 A.

W3 B is an asymmetrically bright shell-like H II region. It is located between the two dense molecular condensations. A bright compact O6 type source IRS 3a is associated with W3 B, which is responsible for ionizing the W3 B H II region. This source is detected only in our H and K_s-band images. W3 B is most likely an emerging blister only partly embedded in the molecular cloud (TGC97).

W3 D is a weak and extended H II region. It is associated with the infrared source IRS 10 (Dyck & Simon 1977). This source is clearly detected in our NIR images. The measured magnitudes for this source are 17.45, 14.86, and 12.98 in J, H, and K-bands, respectively. The color and IR luminosity of this source indicate that it is a B2 type star, which is however not consistent with the spectral type derived from the radio observations (TGC97).

4.6.4. The diffuse H II regions : W3 H, W3 J & W3 K

The diffuse H II region W3 H is located north of the dense molecular gas. The probable exciting star of W3 H is very bright in all the three bands. The color and IR luminosity of this source indicate that it is a B0–B1 type star with a visual extinction of A_V = 6 - 12. We call this source as IRS N2 (see Fig. 4 and Table 1).

W3 J and W3 K are very diffuse and much more dispersed H II regions located toward the south of the W3 Main core. These regions are older than the core regions as lack of dense molecular meterial is seen around them. The ionizing sources of W3 J with spectral type B1–B2 and of W3 K with spectral type B0 may have already dispersed the molecular material. These sources are named as IRS N3 and IRS N4, respectively (see Fig. 4 and Table 1). A concentration of YSOs is seen to the south-east of W3 J where edge-brightening is still observed (TGC97). Most of these YSOs associated with W3 J and W3 K are fainter and have masses lower than the YSOs associated with other compact H II regions.

4.7. Star formation toward W3 Main

The three adjoining regions in the Perseus spiral arm, W3, W4, and W5 are all complexes of active star formation identified by H II regions and aggregates of young stars. Among them the W3 GMC is the youngest. The cluster of compact, ultracompact, and hypercompact H II regions embedded within the W3 molecular cloud appears to be ionized by a recently formed association of O and B stars (TGC97). From our NIR study it appears that the W3 Main region contains both B stars and lower mass stars continuously forming.

It is generally agreed that W4 (= IC 1805), located to the east of W3, was the first of the three large H II regions to be formed and that its expansion might have recently triggered star formation towards the W3 molecular cloud (Elmegreen & Lada 1977, Dickel et al. 1980, Thronson et al. 1985, Carpenter et al. 2000). The close association of the embedded clusters with adjacent H II regions also suggests that triggering may have played an important role in the formation of these clusters (Lada & Lada 2003). The more isolated W5 (= IC 1848), which is found to the east of W4, also shows indications of triggered star formation probably on a lower level (Karr & Martin 2003).

In summary, W3 GMC characterized by H II regions, high mass stars, embedded IR clusters and dense molecular cores, and therefore represents an important source for the study of star formation. Compared with, e.g., the Orion Nebula (O'Dell 2001) and M17 (Jiang et al. 2002) regions, one of the prominent features of the star formation in W3 Main is the absence of dominant OB stars.

5. Conclusions

A deep JHK$_s$-band NIR imaging survey of YSOs associated with the W3 Main star forming region is presented. The survey covers a $4'.9\times4'.9$ area down to a limiting magnitude (10 σ) of J = 19.0, H = 18.1, and K$_s$ = 17.3. From the analysis of these images we derive the following conclusions :

1) A cluster of YSOs (Class II and Class I sources derived from their NIR colors) has been detected in the W3 Main core and near the compact, ultracompact, and diffuse H II regions.

2) A large number of red stars (H-K $>$ 2) are detected in the molecular cloud region, most of them clustered around the molecular clumps associated with IRS 5 and IRS 4. Some of them are also associated with the diffuse emission near the dense molecular clumps. We argue that most of the reddest stars are YSOs with circumstellar materials.

3) The KLF of the W3 Main region shows the power-law slope : $\alpha = 0.26\pm0.02$, which is lower than the typical values reported for the embedded young clusters. Our finding also confirms the previous results of Megeath et al. (1996) for a smaller region around W3 IRS 5.

4) The observed density of the cluster region around W3 IRS 5 is $\sim$ 2000 stars pc^{-3} for K $<$ 17.5, which is larger than the typical values ($\sim$ 1000 stars pc^{-3}) reported for other embedded clusters.

5) Using the age of W3 Main in the range of 0.3–1 Myr determined by Megeath et al. (1996), we find that about 80% of the YSO candidates have an upper mass limit of 4 M$_\odot$. We estimate that the lowest mass limit of Class II & Class I candidates in our observations is 0.1 M$_\odot$. Therefore, the stellar population in W3 Main is primarily composed of low mass PMS stars.

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APPENDIX

Selected interesting regions

In Fig. 10 we present some selected areas of the W3 Main star forming region in our new NIR images that are of noteworthy interest.

(a) About $40''$ south-east of W3 A, a circular bracelike diffuse emission is seen (Fig. 10a). This is probably illuminated by two bright stars of the same luminosity located toward east of this feature. A few YSOs with NIR color excess are located at the southern edge on the bright lane. The dark area is also visible between the bright lane and W3 A, which is seen to the north.

(b) Fig. 10b is a section in the south-east corner of our image, where we detect an H_2 knot reminiscent of Herbig-Haro (HH) object (elongated and bright in K_s-band) which surrounds at least three YSOs. This object was noted already by Tieftrunk et al. (1998). Spectra of this knot/jet and another about $2'$ south-west show H_2 (1-0) S(1) emission and are probably HH-like objects (Tieftrunk et al. 1998). This object is barely detected in the J-band as well. A bright source in K_s-band (K = 12.57, H-K = 1.35) is located at the northern tip of the object. It is, however, striking that no other shock-excited H_2 objects are found in such an active star forming region as W3 Main.

(c) Fig. 10c shows an isolated red source at the center of our image, which is located towards the south-west of IRS 4. The source is clearly resolved into double stars (A and B) separated by $\sim 4''$ in our NIR images. Both these sources are detected only in our H and K_s-band images. The infrared colors of these sources indicate that they are very red objects (H-K = 3.37 for A, and H-K = 2.49 for B). The source A looks extended in the image, probably implying that at 1.6–2.2 μm wavelengths, we are looking at the radiation from an embedded young star scattered by a dusty circumstellar envelope. They are most probably very young stars in their earliest evolutionary phases.

(d) Dark filamentary lanes are seen (Fig. 10d) with irregular shapes which break a more diffuse nebulosity extending throughout the whole W3 Main region. They are associated with the dense molecular gas. An infrared source marked by an arrow with large color excesses (J-H = 4.77, H-K = 2.98) is located inside the dark lanes. This is most probably a young star in its earliest evolutionary phase.

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Table 1: Bright infrared sources associated with the molecular clumps and H II regions

Source	RA (2000)	DEC (2000)	J	H	K	Sp. Type
	hh mm ss	*dd mm ss*	mag	mag	mag	(From CM diagra
IRS 4	02 25 30.97	+62 06 20.9		15.88±0.04	12.96±0.04	O9-B0
IRS 5	02 25 40.76	+62 05 52.5			12.29±0.02	
IRS N1 (W3 E)	02 25 35.15	+62 05 34.8	17.52	13.94±0.02	11.85±0.02	B0
IRS 7 (W3 F)	02 25 40.48	+62 05 40.3		16.33±0.05	13.44±0.03	B0-B1
IRS 2 (W3 A)	02 25 44.43	+62 06 11.7	12.06±0.03	10.04±0.03	8.85±0.03	O5-O6
IRS 2a (W3 A)	02 25 43.34	+62 06 15.4	12.68	11.54±0.06	9.80	O5-O6
IRS 2b (W3 A)	02 25 41.74	+62 06 24.5	13.64±0.06	11.36±0.06	9.86±0.05	O6
IRS 2c (W3 A)	02 25 47.09	+62 06 13.1	13.49	11.45	10.19±0.04	O9-B0
IRS 3a (W3 B)	02 25 37.83	+62 05 52.1		15.12±0.02	12.19±0.02	O6
IRS 10 (W3 D)	02 25 29.80	+62 06 31.8	17.45±0.05	14.86±0.02	12.98±0.02	B2
IRS N2 (W3 H)	02 25 32.60	+62 06 59.7	11.69±0.02	10.49±0.03	9.78±0.02	B0-B1
IRS N3 (W3 J)	02 25 27.35	+62 03 43.4	11.22±0.02	10.45±0.02	9.99±0.02	B1-B2
IRS N4 (W3 K)	02 25 44.85	+62 03 41.3	10.19±0.02	9.35±0.02	8.90±0.02	B0

Table 2: Power-law fits to KLFs in W3 Main

Region	α
Cluster	0.17±0.02
Whole W3	0.26±0.01
Whole W3 - Cluster	0.28±0.02

Fig. 1.— J, H, and K_s-band images of the W3 Main star forming region displayed in a logarithmic intensity scale. The circle of a radius of $30''$ (0.27 pc) marked in the H-band image shows the cluster region around W3 IRS 5. The locations of the individual H II, UC H II regions, and the embedded IR sources are marked in the K_s-band image. North is up and east is to the left. The abscissa and the ordinate are in J2000.0 epoch.

Fig. 2.— JHK$_s$ three-color composite image of the W3 Main star forming region (J: blue, H: green, K$_s$: red) obtained by SIRIUS mounted on the UH 2.2 m telescope. The field of view is $\sim 4'.9 \times 4'.9$. North is up and east is to the left.

Fig. 3.— Color-color diagrams of (a) the W3 Main star forming region and (b) the reference field for the unsaturated sources ($K_s > 12$) detected in JHK$_s$-bands with photometric errors less than 0.1 mag. In (a), open squares show the saturated SIRIUS sources ($K_s < 12$), which have been replaced by the corresponding 2MASS sources. Open triangles indicate 2MASS sources with upper limits in magnitudes. A gap is seen between the reddened stars and unreddended stars (located near the main-sequence locus : H-K $\sim$ 0.4, J-H $\sim$ 1.0). The sequences for field dwarfs (solid curve) and giants (thick dashed curve) are from Bessell & Brett (1988). The dotted line represents the locus of T-Tauri stars (Meyer et al. 1997). Dashed straight lines represent the reddening vectors (Rieke & Lebofsky, 1985). The crosses on the dashed lines are separated by $A_V = 5$ mag.

Fig. 4.— Color-magnitude diagram for the sources detected in H and K_s-bands with photometric errors less than 0.1 mag. The open squares show the saturated SIRIUS sources (K_s < 12), which have been replaced by the 2MASS data. The open triangles indicate 2MASS sources with upper limits in magnitudes. Stars and filled triangles represent the YSOs identified from the regions T and P in Fig. 3a, respectively. The vertical solid lines from left to right indicate the main sequence track at 1.83 kpc reddened by A_V = 0, 20, 40, and 60 magnitudes, respectively. The intrinsic colors are taken from Koornneef (1983). Slanting horizontal lines identify the reddening vectors (Rieke & Lebofsky 1985). Also shown are the positions of known IRS sources.

Fig. 5.— Spatial distribution of the YSO candidates superposed on the K_s-band image with a logarithmic intensity scale. Stars represent T-Tauri sources (Class II), filled triangles indicate Class I sources, and filled circles denote the red sources (H-K > 2). The abscissa and the ordinate are in J2000.0 epoch.

Fig. 6.— The rms error in the magnitude of the recovered fake stars for the cluster and whole W3 regions, respectively.

Fig. 7.— (a) and (c) The raw K_s-band luminosity functions for the cluster and whole W3 regions, respectively. The error bars correspond to $\pm\sqrt(N)$, where N is the number of stars in each magnitude bin. (b) and (d) The detection completeness as a function of magnitude for the cluster and whole W3 regions, respectively. The error bars are shown as $\pm 1\ \sigma$ of the mean of 8 trials performed in each magnitude bin.

Fig. 8.— (a) and (c) The corrected K_s-band luminosity functions for the cluster and whole W3 regions, respectively. The dotted lines show the KLFs corrected only for the completeness. The dashed lines denote the field star counts from the reference field corrected for the completeness and modified to reflect the unextincted foreground stars and background stars reddended by A_V= 30 (A_K = 3.36), with the help of the galactic model (Wainscoat et al. 1992). The solid lines correspond to the field star subtracted KLFs. (b) and (d) The completeness-corrected and field star-subtracted KLFs of the cluster and whole W3 regions, respectively. The solid lines are the best linear fit to the data points.

Fig. 9.— Color-magnitude diagram for the YSO candidates in W3 Main. Class II candidates are indicated by stars, filled triangles represent Class I candidates, and the filled circles are red sources with H-K $>$ 2 having J counterparts. The solid curve denotes the loci of 10^6 yr old PMS stars, and the dotted curve for those of 0.3×10^6 yr old ones, both derived from the model of Palla & Stahler (1999). Masses range from 0.1 to 4 $M_\odot$ from bottom to top, for both curves. The solid oblique reddening line denotes position of PMS with 2 $M_\odot$ for 1 Myr and the dotted oblique lines denote positions of PMS with 2 and 4 $M_\odot$ for 0.3 Myr, respectively, in this diagram. Most of the objects well above the PMS tracks are luminous and massive ZAMS stars (see Table 1 and Fig. 4).

Fig. 10.— Enlarged view of the color image of selected areas (see Fig. 2 and Appendix). a) a circular bracelike diffuse emission probably illuminated by two bright stars of the same luminosity located toward east of this feature. b) H_2 knot reminiscent of HH object which surrounds at least three YSOs. c) an isolated red source at the center of the image, which is located towards the south-west of IRS 4. The source is resolved into double stars separated by $\sim 4''$. d) dark filamentary lanes with irregular shapes. An infrared source, marked by an arrow, with large color excesses is located inside one of them.

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